Integrated Plant monitoring to improve plant operation strategy and results

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Abstract

The more and more demanding conditions in the power generation sector requires to apply all the available technologies to optimize processes and reduce costs. An integrated asset management strategy, combining technical analysis and operation and maintenance management can help to improve plant performance, flexibility and reliability. In order to deploy such a model it is necessary to combine plant data and specific equipment condition information, with different systems devoted to analyze performance and equipment condition, and take advantage of the results to support operation and maintenance decisions. This model that has been dealt in certain detail for electricity transmission and distribution networks, is not yet broadly extended in the power generation sector, as proposed in this study for the case of a combined power plant. Its application would turn in direct benefit for the operation and maintenance and for the interaction to the energy market.

Key Words

Combined cycle power plant, monitoring, data management, data integration

Nomenclature

APM Asset Performance Management

CMMS Computerized Maintenance Management System

DCS Distributed Control System

ERP Enterprise Resources Planning System

HRSG Heat Recovery Steam Generator

IPM Integrated Plant Management

KPI Key Performance Indicator

LIMS Laboratory Information Management System

MSET Multivariate State Estimation Techniques

O&M Operation and Maintenance

OPC Open Process Control

PIMS Plant Information Management System

PLC Programmable Logic Controllers

RUL Remaining Useful Life

SCADA Supervisory Control And Data Acquisition

SNMP Simple Network Management Protocol

TCP Transmission Control Protocol

1 Intro

The Power Generation sector has drastically evolved in the last decades due to significant technological and regulatory changes, that have completely transformed the business paradigms. In the last fifteen years the electric sector has moved from a public service to a highly competitive market subjected to strict environmental requirements and in the most recent years, to the over capacity [1] . All that comes together with a technological evolution that has introduced renewable generation technologies in the scene with a significant contribution to the generation.

In this environment, the flexibility to follow market requirements and the optimization of the operation costs are key drivers to make profit from the existing installations. An integrated Asset Management strategy contributes to rationalize operation, and especially maintenance costs, as introduced by [2] and [3] for the electricity transmission and distribution (T&D) sector or by [4] for the nuclear power generation.

The improvement in monitoring technologies [3][5], many of them available for online analysis, on communications, data management and analytics allows an integrated asset management based on actual equipment condition and supported by predictive analysis, considering process and market aspects.

This paper proposes an integrated management strategy, combining technical analysis results to the power generation key processes (operation and maintenance) management. A gas turbine combined cycle is selected to illustrate the concept that could be easily extended to other generation technologies.

2 Power Generation Value Chain

For a power plant in the operation phase, the business process can be summarized, according to Figure 1, in scheduling, production and settlement.

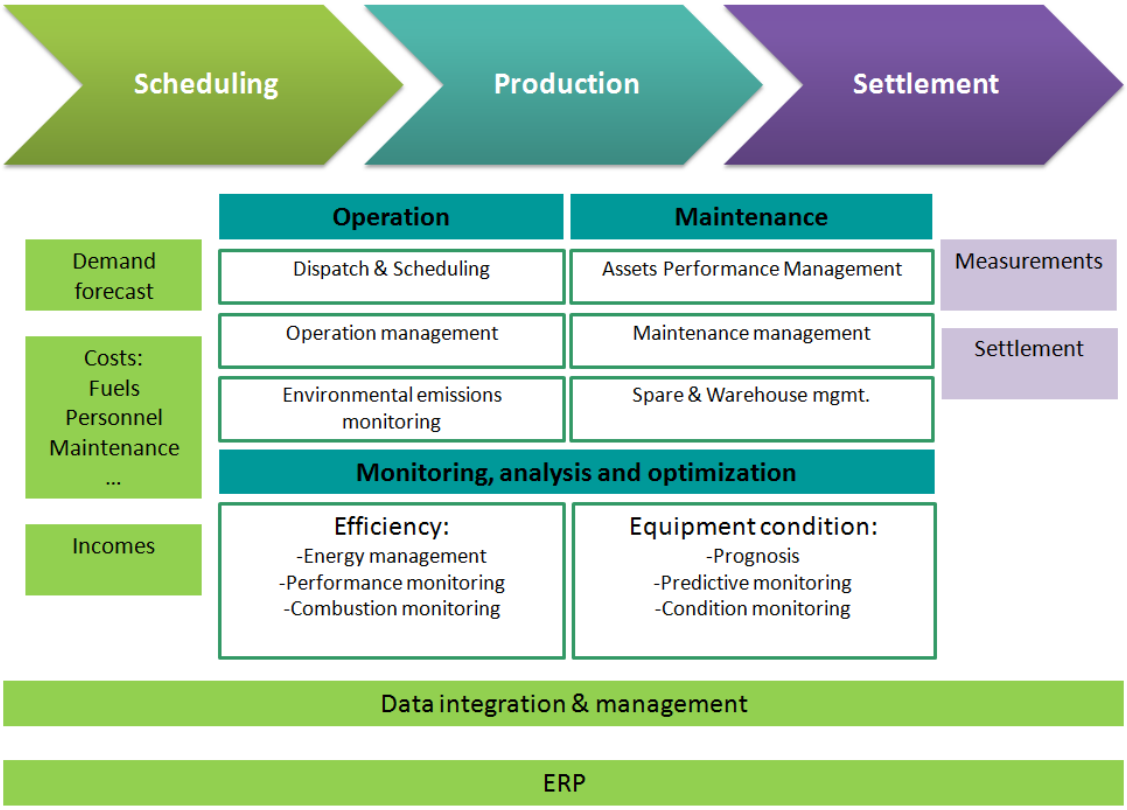

Figure 1: Power generation plant business process

Planning the generation programs, and the resources needed to accomplish them with the highest possible accuracy is a starting step for a successful business result. It allows the most effective maintenance actions and unavailability periods to reduce cost and maximize output. As well, when dealing with a fleet, managing the plants performance can help gain additional value.

Settlement, rather than being an aspect linked to the plant state, serves as analysis point and input to improve the future planning.

Within the production phase, we are grouping the processes in operation, analysis and maintenance. Analysis is, at the end of the day, a set of activities and functions that help support and improve the operation and maintenance.

We propose a basic classification of the analysis in techniques related to efficiency and those linked to the asset condition monitoring. More detail about the considered technologies is included in the following section.

3 Integrated Plant Management

The Integrated Plant Management (IPM) concept combines the results of monitoring and technical analysis of different aspects linked to the power plants performance and condition with the operation and maintenance (O&M) process management and optimization.

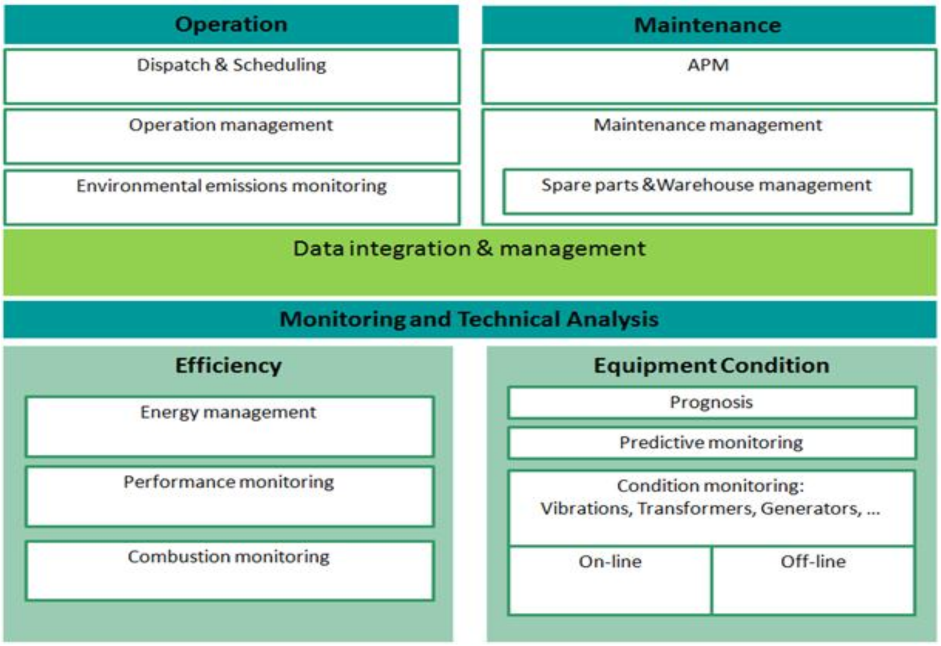

Figure 2: Power generation plant business process

The link between the monitoring and analysis and the O&M management is the plant information management system (PIMS) that gathers, integrates and manages information from different sources, feeds it to the systems involved in the IPM and allows queries, reporting, and analysis, as described in a specific section.

Apart from the data integration and management system, there are three main blocks of systems defined within the IPM:

- Operation Management
- Maintenance Management
- Monitoring and Technical Analysis

The **Operation Management** block comprises the systems needed to support the operation process. The following modules are included here: the generation program and generation plan follow-up, an operation management system, the environmental emissions monitoring and reporting and the fuels management system, when applicable.

The **Maintenance Management** block covers the systems required to perform the maintenance planning, execution and optimization. On the first stage, it is the maintenance management system that represents the traditional computerized maintenance management system (CMMS). The spare parts and warehouse management, that can also be considered as a subsystem or functionality of the CMMS, is included in this block too. Finally, the most recent Asset Performance Management (APM) systems [6] have been included on the top of the previous ones, since they support advance management strategies implementation and the optimization of the maintenance process.

Within the Monitoring and Technical Analysis block, two groups of technologies are distinguished, first, those oriented to monitor energy efficiency and performance, and secondly, those devoted to identify and predict the equipment condition. Those blocks and their components are described in detail in the following sections, as well as the most relevant point, the integration model between the different systems.

3.1 Efficiency analysis technologies

Within the efficiency analysis section we are grouping those techniques and technologies oriented to improve the performance of the installation by getting most from the primary energy source (natural gas in the case of gas turbine combined cycles) transformed into electricity. This can be achieved by improving the process itself and by the reduction of auxiliary energy consumption.

3.1.1 Energy efficiency management

Although energy management has a higher relevance in industry and building sectors, we are briefly covering it here as well.

First, as energy efficiency monitoring, we understand the calculation of the ratio of produced versus consumed energy (fuels, heat, electricity,…) along the installation. For the combined cycle power plant case, and if we skip what we will cover within the thermal performance monitoring, the energy efficiency monitoring will track the electric consumptions along the plant, especially, for big electric equipment, mainly pumps or compressors.

This consumption monitoring can be done as easily as calculating the energy balance based on specific data sets. Setting target or reference values and upper limits linked to alarms can be helpful to get an easier assessment of the plant electric consumption. Of course there are also specific tools available, but they are oftener used at complex processes, as in the chemical or oil and gas industry. If deviations are identified an investigation about the cause would be open to drive the equipment again to its optimal performance point.

The improvement of energy efficiency in a combined cycle power plant could be partially done through operational changes (especially during the start-ups or when the plant is not generating energy), but in many cases, it is linked to improvements in the equipment themselves.

3.1.2 Performance monitoring

Performance monitoring is the process of continuously evaluating the production capability and efficiency of a unit over time using on-line measured plant data [7]. The main purpose of a performance monitoring system is to provide detailed information of the plant and equipment performance to allow taking actions to operate and maintain the plant at its optimum performance.

It implies the calculation of the thermodynamic balance for the complete process, but also for the main equipment (turbines, compressors, HRSG, condenser, pumps, …). The calculated actual performance is compared to a reference or optimum balance, that can be estimated in several ways. Some options to calculate the reference are, design data, performance test data, operational data benchmark, or a similar plant reference data. Ideally, as actually some existing tools do, the reference data have to be defined taking into account the operational and boundary conditions.

The deviations between actual and reference values allow to identify equipment degradations and miss-performance, as well as problems with the instrumentation. Accordingly, the plant operator can make decisions on operation and maintenance to drive the equipment to the optimum performance in the shortest feasible time.

To perform that analysis the performance monitoring systems generally consist of two main modules:

Modeling environment: it consists of a calculation engine capable of simulating the plant steady-state energy balance under different operating and ambient conditions. The model is based on thermodynamic first-principles. The user can set-up and maintain the thermodynamic models from a library of components typically present at power plants.

Monitoring environment: this module includes the required tools to perform the on-line calculation of the thermodynamic plant balance from the available instrumentation, compare it to the "optimum balance" and identify deviations.

These systems include also other functional modules, like the interface to plant data, data validation or reconciliation, a data base, reporting, different options of user interface or data export.

3.2 Equipment condition analysis technologies

Several technologies target to identify, characterize and foresee the condition of the equipment are dealt within this section. Different criteria are found along the literature to define the available technologies related to the characterization of the current and future condition of the assets. The assumptions applied in this article are based on the definition of monitoring, diagnosis, prediction and prognosis in a general sense. [14].

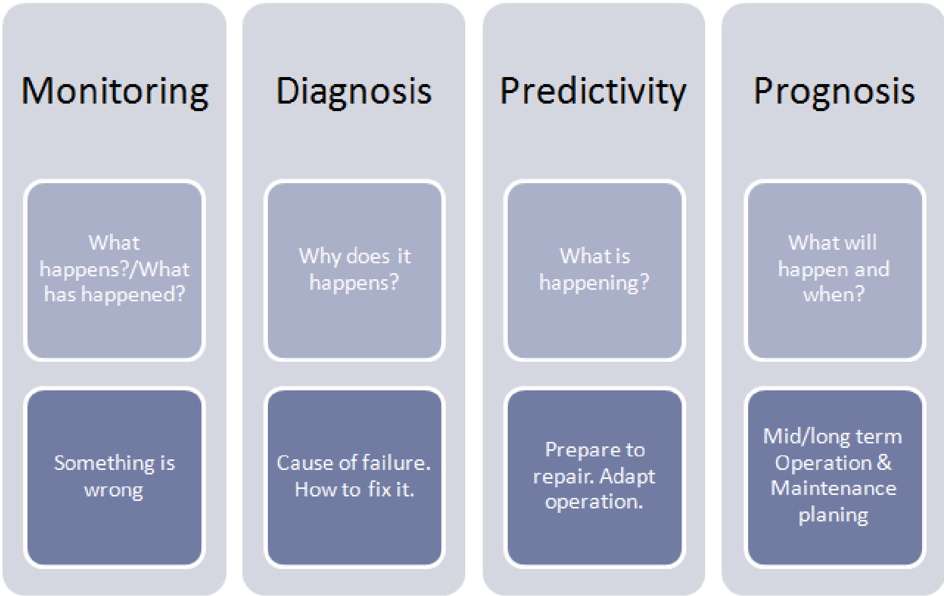

Figure 3: Equipment condition analysis stages

Hence, we are going to refer to **monitoring** for those techniques and systems that shows the actual state of the data related to certain equipment or process, **diagnosis** when a system or technique helps to identify the causes and the severity of a failure or visible degradation in an equipment, **predictive analysis**, those that identify degradations before the failure takes place, giving the choice to modify the operation mode and maintenance actions to avoid the failure and collateral damage to other equipment. Finally, we will speak about **prognosis**, for the kind of analysis that predicts the state of the assets in the future, assessing the risk of failure in a certain time window that can vary from weeks to few years.

Due to the huge multiplicity of available technologies [14], in the study, only a general overview of the main techniques is included, and the selection is based on the more extended ones for the main equipment in power generation plants.

3.2.1 Condition Monitoring

[9] **Condition monitoring** is the process of monitoring a parameter of condition in machinery (vibration, temperature etc.), in order to identify a significant change which is indicative of a developing fault. It is a major component of condition based and predictive maintenance. The use of condition monitoring allows maintenance to be scheduled, or other actions to be taken to prevent failure and avoid its consequences. Condition monitoring contributes to avoid or minimize the evolution of phenomena that would shorten normal lifespan, taking action before they develop into a major failure.

Condition parameters are a group of characteristics that indicate equipment condition. These characteristics, such as vibrations and temperatures, usually remain stable as long as the equipment is healthy.

Some examples of condition monitoring techniques for different equipment present at power plants are vibrations analysis, oil analysis, gases dissolved in oil analysis, partial discharges analysis, short cut analysis, acoustic analysis, thermography, radiography, visual inspections, corrosion analysis, etc.

Condition monitoring can be performed periodically or on-line. Accordingly, data can be generated off-line or on-line. In the case of periodic off-line analysis, to perform an integrated plant management, it is recommended to digitalize and systematically manage the information to allow its review, comparison and integration with other systems. This can be done combining documentation management systems with the extraction of key parameters to the PIMS.

Over the last years, many of the above mentioned technologies have evolved and on-line monitoring devices have been developed. The primary measurements are treated with specific analysis systems to provide information about the equipment condition.

For on-line data it is relatively simple to integrate them in the PIMS, allowing easily tracking and using them. The data integrated in PIMS can be the raw sensors measurements, or certain elaborated parameters that represent the condition of the equipment.

3.2.2 Predictive Monitoring

Predictive analytics allows identifying certain patterns in a data set. Applied to identify early degradation and impelling failures, this technique has proved to be extremely effective. There is not a clear academic definition, but when predictive analytics are performed on real time, allowing on-line analysis of the equipment state, is known as "predictive monitoring" [12].

Predictive analytics is a technology based on data, experimental data, and hence is very flexible to adapt to different sectors or technologies. Here of course, we are going to focus on the application to power generation equipment health assessment.

The main targets of the predictive monitoring systems are [10] to detect and identify incipient disturbances sufficiently early to avoid forced shut-downs and physical damage. In short, to detect disturbances so that necessary repairs can be scheduled and performed at a time convenient to plant operational requirements.

[10] [11] [12] On-line sensors validation and provision of "virtual" sensors for replacement of failed sensors, and diagnosis of disturbances are significant applications of predictive monitoring as well.

A key factor that differentiates predictive monitoring from the above mentioned condition monitoring techniques is that the predictive monitoring works with the available data, whichever origin they have, as long as they characterize the equipment performance or condition and correlate to each other.

The data used for the predictive monitoring in a combined cycle power plant can be process and control data from the distributed control system (DCS), environmental data, or even data coming from condition monitoring systems, for example vibrations for the rotating equipment or gases dissolved in oil for the transformers.

Normally, predictive monitoring systems work with the available information and do not need additional instrumentation to be installed at the plant. On the contrary, the condition monitoring systems are focused on specific phenomena and require the installation of instrumentation and often, additional components to gather and process that information.

Other difference between both technology groups is that while condition monitoring techniques are rather specific, focusing on certain degradations or failures that are linked to the equipment (we can say that they somehow zoom on specific phenomena to identify detailed problems), the predictive monitoring provides a wide analysis using any data available, as long as it is linked to the equipment performance and condition.

All these make both technologies complementary, being the experience at power plants that the predictive monitoring provides earlier identification while condition monitoring (for example, vibrations analysis), provides a detailed insight to diagnose and follow the evolution of mis-performance, according to the users of these kind of solutions.

The monitoring and diagnostic systems [10] use a model of the process to estimate its operational estate, make a measurement of the current operation state and to analyze the difference between the estimate and measurement to determine if such differences are due to normal statistical fluctuations or if a real disturbance is manifesting itself.

As explained in [12], the overall diagnostic procedure consists of a training step, used to characterize the monitored asset based on historical operation data [10] (normal operation data) and a monitoring step, where the actual operation data are compared [11] to an expected estimate of the current state of the system, obtained from the historical normal data set applying advanced pattern recognition techniques.

The mathematical technology on which the predictive monitoring relies is a group of advanced empirical techniques, that can be parametric or non-parametric. Some of the most common ones are the Multivariate State Estimation Techniques (MSET), that are broadly described in the literature [10], [11].

Artificial intelligence techniques, like neural networks have been also explored and applied [8], but the difficulty of obtaining the required training data makes them less effective.

3.2.3 Equipment condition prognosis

Prognosis is the forecasting or making a prediction about how something will develop. When applied to assets condition, there are two main types of prognosis [8], the first one , and most extended, is to predict the remaining time before a failure occurs given the current machine and past operation profile. The time before the failure takes place is known as remaining useful life (RUL).

The second type consists of predicting the chance that a machine operates without a fault or failure up to some future time, given the current machine condition and past operation profile.

The aim of the prognosis is to provide objective information to make decisions about when to perform maintenance activities, what actions to develop and to make decisions about equipment refurbishing or replacement.

A prognosis system combines [13] the monitoring of operational data, boundary conditions, such as ambient conditions , and asset health with a forecast model that prognoses the evolution of the asset condition based on the current state and the operating conditions expected for the time period under analysis.

Following [8], three different approaches to prognosis can be defined: statistical approaches, artificial intelligence approaches and model-based approaches.

In the prognosis process, [8] multiple sensors and data are combined, but also different condition techniques as proposed in [14].

For the power generation industry, [15] the prognosis can be applied from the component level (pumps, turbines, compressors,…) to the unit level and to the fleet level.

3.3 Data integration & management

To close the description of the different pieces considered in the IPM a data integration and management system allows to read data associated to variables from different sources, store them in an efficient way, and support queries, reporting and different ways of visualizing the information stored. According to [16], a Plant Information Management System (PIMS) gathers and integrates information from different sources. The data integration and management is considered the core application to integrate the data and the different analysis and management solutions used at the power plant.

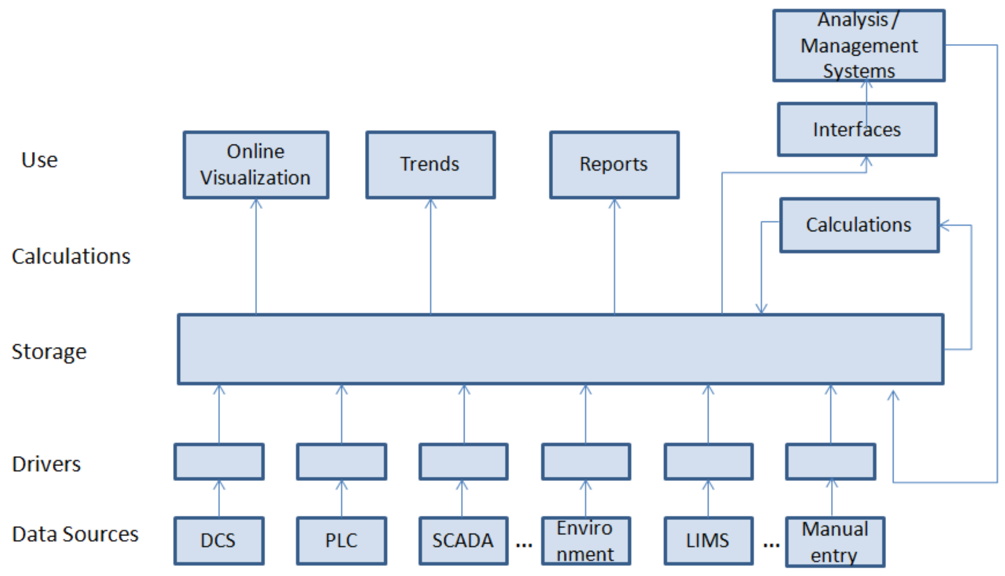

Figure 4: PIMS basic scheme

[17] Sensors and actuators are used on real time to operate plants. Beside the operational use, sensors data can be used to extract useful information for plant optimization, failures anticipation, etc.

Additionally to the sensors and actuators required for operation control, the installation of on-line devices to monitor the condition of the equipment is getting a more relevant role every day, as said before.

Other data sources can be the laboratory information management system (LIMS), environmental emissions measurements or even manual data entries, for example to record manual sets of data coming from operator rounds. In this sense, the PIMS serves as an intermediate layer between condition monitoring and CMMS and enterprise resources planning system (ERP) that also integrate event data as suggested by [14].

Connection to data sources is solved through different drivers[18], Open Process Control (OPC) and Fieldbus [19], TCP, Modbus, SNMP, or other specific drivers developed to connect with supervisory, control and data acquisition (SCADA) systems, etc. In the case of power generation plants, the DCS is the main source of process data.

Single data parameters are usually called tags. Tags values are stored following certain logic, as at each modification, or with a sampling interval [17]. Acquired data are stored in a data base. To make an effective use of the storage volume, it is possible to apply truncation or compression algorithms. The frequency of data storage is limited by the original data sampling frequency and typical refreshing times go from 1 second to 1 minute. This parameter can be also configured particularly for every tag.

Traditionally, information from different sources has remained isolated. The integration of the sensors installed at the plant in the PIMS allows the information to be accessible for general and consistent use along the company and also makes it available for integration in different applications and systems.

To improve the data quality, data validation and reconciliation techniques can be applied. Data validation applies simple rules to check data quality, as for example maximum and minimum values, non zero data or non plain data, etc. Data reconciliation adjusts the values so that the corrected ones are consistent with the corresponding balances [23], based on information contained in the process measurements and models.

Examples of use of the data are [17] equipment monitoring, maintenance support, statistics publication, compliance with environmental regulation, results reporting, etc. Data can also be analyzed through data mining techniques with very different purposes.

According to [20], the volume of data managed for predictive analysis is doubling every two years. In 2012, [21] states that the volume of generated data was 2,8 zettabytes (1E21 bytes), but only 0.5% of them were used for analysis. Forecast following [21] is to reach 40 ZB generated in 2020. To deal with such a volume of data, traditional data management systems are no longer valid, and **Big Data** technology takes a relevant role on the stage. It is especially important when we move to fleet analysis and when plant, market and business data are analyzed in combination.

4 How the different technologies integrate to each other

The integration of the meaningful data between the different management and analysis systems in order to assure an operation and maintenance management based on actual equipment condition and predictive analysis results is already under development in some pioneer projects, but neither broadly extended, nor reported. Considering the crossed impact of the decisions on operation and maintenance issues over the performance and equipment condition and the opposite, IPM provides a significant opportunity of optimizing power generation plants results.

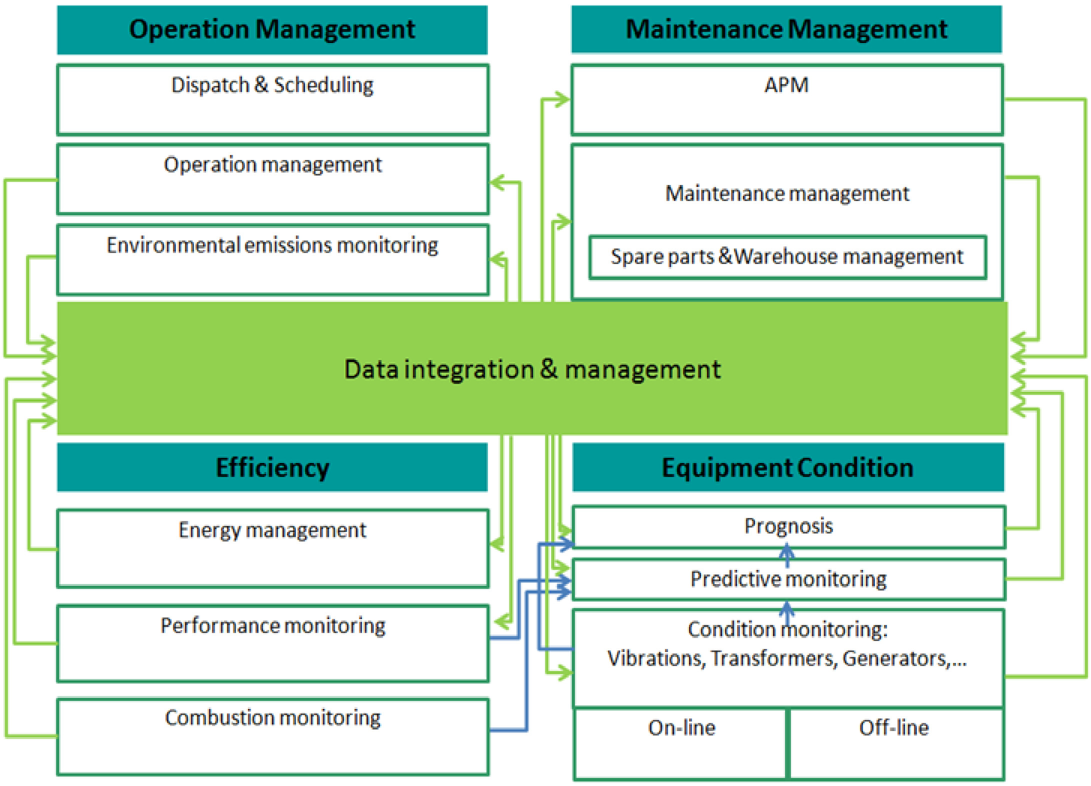

Figure 5: Integration between the different management and analysis modules

Regardless that in certain cases, a direct integration between specific modules could be desirable, the PIMS will be considered as the central repository and connection point between them. The PIMS includes the relevant process and control data coming from the distributed control system (DCS), a selection of results coming from the analysis and management systems and other sources, as can be the laboratory management system (LIMS), or environmental data.

In the drawing, some integration lines between modules have been included for conceptual evidence, but it does not necessarily mean that those connections are being performed independently from the PIMS.

The **integrations within the equipment condition block** (besides the reading of plant data through the PIMS) include the use of certain results of the condition monitoring solutions to the predictive monitoring system. Some examples are the vibrations analysis results (for example the first, second and third harmonic values, or the acceleration), that add significant information to analyze the mechanical state of rotating equipment. The use of tags related to the gases dissolved in oil for the transformers, either as individual gases concentration or as a synthetic index improves the capability of early detection of degradations, by putting the information in context with other operational parameters.

The results of both, condition monitoring and predictive monitoring systems are relevant inputs for the prognosis analysis, that takes them into account to estimate the risk of unavailability in a near and midterm, based on the evolution of the equipment condition, the operation and use it is submitted to and historical patterns among others.

The predictive monitoring module is especially useful to provide integrated analysis of different kind of information to detect deviations from the normal behavior . Accordingly, it shows an improvement of results when thermal performance results, for example, steam turbine, pumps or heat exchangers performance are included in the predictive monitoring system.

Within the efficiency analysis technology, no choice to get value from integration from one to the other has been found. As mentioned, it is interesting to integrate results from the performance monitoring to the predictive monitoring, and of course the reading of data from the PIMS.

Once covered the main integrations within the technical analysis blocks, we can move to the integrations with the O&M management systems. As in the other cases, the PIMS serves as source of data to the different modules and repository of the most relevant results of the systems.

The maintenance management system can efficiently and consistently perform a preventive maintenance plan thanks to the automatic reading of plant operation data. The running operating hours or even more elaborated rules, including time spent over a certain load or number of start-ups for certain equipment can be automatically followed and fire work orders included in the preventive maintenance plans.

A more sophisticated application would be the use of alerts associated to the condition monitoring and predictive monitoring systems to launch work requests. In that case a predictive maintenance strategy would be automatically supported.

The APM system can be integrated with the CMMS to share the assets hierarchy, to analyze the maintenance plans and to modify the maintenance plans according to the results of the maintenance optimization analysis.

Apart of the integration to the CMMS, it makes sense to integrate the APM system to the condition monitoring, the predictive monitoring and the prognosis systems, to automatically get the results of the mentioned solutions. That does not mean that a specific connection is needed, since that integration can typically be solved through the PIMS.

Also between the O&M management systems exists meaningful integrations. The most important is the integration of the operation management system and the CMMS. The aims are first, the use of a common asset hierarchy and the consistent definition of some procedures that involve both the Operation and Maintenance areas, as for example, the work permits to assure the compliance with all the safety and work execution requirements, linked to the maintenance activities. As mentioned in [3-Fig 6] the operational incidents content in the operation management system are relevant to perform analysis on the effectiveness and impact of the maintenance management. Hence that integration can be relevant to the CMMS and the APM.

Finally, sending relevant results and KPI´s from the O&M management systems to the PIMS facilitates combined analysis and visualization of the complete process linked the power plant operation.

5 What does it bring to the operation results

A qualitative description of the advantages expected at a combined power plant by approaching the operation and maintenance management based on the IPM is described here.

The benefits are classified based on the impact on three main processes, the plant operation, the plant maintenance and the interaction with the electric market.

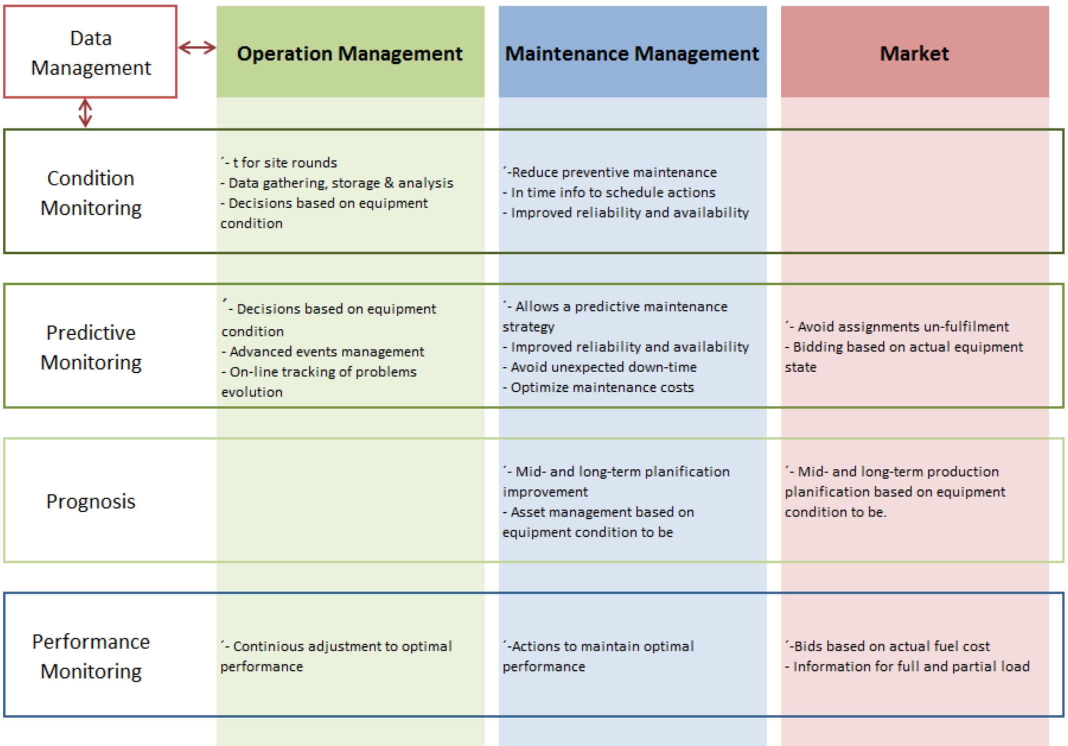

Figure 2: Impact of the IPM in power generation business process

The integration between the condition monitoring and the operation management allows first of all an improvement in the work efficiency due to the reduction of time needed to perform plant rounds, once that some of the measurements traditionally included in the rounds are automatically recorded and processed.

Most important is the fact of making operation decisions based on actual equipment condition, for example, the selection of redundant pumps according to their actual state, identified by vibrations or electric wave form analysis [22].

The predictive monitoring enhances the capability of making decisions on the operation side compared to the condition monitoring, especially because of the anticipation gained with these systems compared to condition monitoring ones. It is also a plus getting a detailed on-line insight of the degradations detected in early stages, showed by severity index.

The detection of operational errors is quite often done by the predictive monitoring. Although in another way, the performance monitoring can also identify malfunctions or operational and control settings mismatches, that would not be otherwise detected with the control system.

To finalize the benefits gained on the operation, the results of the performance monitoring, that normally show the equipment in the process that are contributing to mis-performance, allow the operator to take decisions to drive the plant to its optimal thermal performance in real time.

In the maintenance process there is a common benefit from all the equipment condition systems, that is the improvement of reliability and availability, together with a reduction on maintenance costs, mainly due to a better works planning and avoidance of collateral damages.

The different contribution of the condition monitoring, predictive monitoring and prognosis is, as covered in Figure 3, is the time frame that moves from the current moment (monitoring), the short term (predictive) to the mid or log term for the prognosis. As well, the detailed analysis of the causes and progression of the degradation, moves on the opposite way, providing the condition monitoring techniques, the highest detail.

6 Summary and conclusions

Current situation of the energy market in Europe, operated with a daily pool, subjected to strict environmental regulations, and suffering low operating hours due to installed overcapacity [1] requires the power generation plants to improve their flexibility and reduce costs to be proficient.

This article suggests the implementation of an integrated plant management model (IPM) for the combined cycle power plants, combining technical analysis to the operation and maintenance management process to help reach those targets, in a similar way as suggested by [2] and [3] for the transmission and distribution sector or by [4] for the nuclear power generation.

In the operation and maintenance management blocks the operation management and the interaction to the energy market, the maintenance management system and the advanced asset performance management [6] systems are considered. The novelty is to integrate the results of the technical analysis systems in both the operation and maintenance processes.

Two main blocks are considered within the technical analysis. First the efficiency modules, where the performance monitoring outstands for combined cycles. Secondly, the condition analysis systems, ranging from condition monitoring techniques [3], to predictive monitoring [10] and prognosis [15] that cover the supervision, analysis and foreseen of the equipment condition with a decreasing detail, but a broader perspective and longer temporally spectrum.

The plant information management system PIMS serves as core of the model, gathering the information from the plant and the different systems [18] and allowing the interchange of data among the different systems, beside its traditional functionalities [16].

The application of the suggested model impacts on the operation, the interaction to the energy market and the plant maintenance, improving the efficiency, reliability and availability, reducing the risk and reducing as well the maintenance costs.

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